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[illegible] digital imagery are being investigated. This report gives the results of the application of test models using Landsat TM imagery.

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Executive Summary

Water depths in the near-shore zone of western Isla de Vieques are calculated using Landsat 4 Thematic Mapper imagery and two different algorithms. The first is a new algorithm that does not require a sea-bottom-type clustering; the second is the dual-band-ratio algorithm. TM bands one and two (0.45–0.52 μm and 0.52–0.60 μm, respectively) are water penetrating and provide capability for calculating water depths to about 20 m in clear water. A comparison of results of remotely sensed bathymetry using the two different models is made.

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Contents

A Comparison of Models for Remotely Sensed Bathymetry

Introduction

Remotely sensed bathymetry from multispectral imagery has been studied for several years.[1-3] Three models have been devised to enable calculation of water depth, the so-called single-band algorithm,[4] the two-band ratio method,[5] and the multiband method.[6] The first two models have the disadvantage of requiring a bottom-type clustering to minimize the bottom reflectance variation. The third model requires many (>2) water-penetrating bands, because present sensors are predominantly optimized for land remote sensing and do not have sufficient water-penetrating bands to satisfy this model.

The single-band algorithm and the dual-band ratio method have been tested with good results.[7-9] However, a new algorithm we call the linear multiband method has recently been introduced[10] that does not require a bottom-type clustering. This new algorithm holds the promise of yielding absolute bathymetry in cases where the number of different bottom types is equal to or less than the number of water-penetrating bands in the imagery.

We recently tested the linear multiband method using bands one and two of Landsat Thematic Mapper imagery in the vicinity of Isla de Vieques. The results are compared to bathymetric measurements made using the dual-band ratio method. The calibration data used in both methods were taken from a 1:25000 combat chart of the region. With the linear multiband algorithm we achieved improved results without performing the time-consuming process of bottom-type clustering and classification required by the dual-band ratio model.

Background

Remotely sensed bathymetry from multispectral imagery generally is based upon a simple reflectance model;[4] the radiance in wavelength band i at water depth z is given by

$$L_i = L_{i\infty} + c_i R_{ai} \exp(-2k_i Z),$$

where L_i is the radiance value in band i, $L_{i\infty}$ is the average signal over deep water, c_i is a constant that is a function of several optical parameters, R_{ai} is the bottom reflectance in band i over bottom type a, and k_i is the diffuse attenuation coefficient.

Solving for z, one obtains the formula

$$Z = LN(c_i R_{ai})/2k_i - X_i/2k_i$$

where we have adopted the convention that $X_i = LN(L_i - L_\infty)$.

This single-band reflectance model assumes that the bottom reflectance is constant over the bottom type, that the atmosphere and the sea state are uniform, and that other background optical effects are either uniform or constant throughout the image.

To reduce errors due to the variation of the bottom reflectances, a two-band ratio method (or dual-band method) was devised.[5] In this algorithm, the depth is given by

$$Z = (1/2(k_1 - k_2))(LN(c_1 R_{a1}/c_2 R_{a2}) + X_1 - X_2)$$

where the subscripts 1 and 2 indicate different bands. In this method, we assume that changes in the bottom reflectances occur in such a way that the ratio $c_1 R_{a1}/c_2 R_{a2}$ remains constant.

Another method, which we call the linear multiband method, gives the depth by

$$Z = \sum \omega_i (1/2k_i)(LN(c_i R_{ai}) - X_i)$$

where the sum is taken over several bands and the weights ω_i satisfy the constraint that $\Sigma \omega_i = 1$. Paredes and Spero,[7] generalizing the assumption that the ratio $c_1 R_{a1}/c_2 R_{a2}$ remains constant, assume there are constants ς_i and α independent of bottom type such that

$$(c_1 R_{a1})^{\varsigma_1}(c_2 R_{a2})^{\varsigma_2}(c_3 R_{a3})^{\varsigma_3} \ldots =$$

$$(c_1 R_{b1})^{\varsigma_1}(c_2 R_{b2})^{\varsigma_2}(c_3 R_{b3})^{\varsigma_3} \ldots =$$

$$\ldots = \alpha$$

With this assumption, they show that certain weights, ω_i can be found such that, when used in the above multiband linear depth equation, produce an equation for Z independent of the bottom reflectance and depend only upon the values ς_i:

$$Z = (1/2 \sum_{\varsigma_i} k_i)(1 - \varsigma_1 X_1 - \varsigma_2 X_2 \cdots).$$

Alternatively, this equation may be written

$$Z = A_0 + A_1 X_1 + A_2 X_2 + \cdots + A_n X_n,$$

where the coefficients $A_0, A_1, \cdots, A_n$ are constants independent of the bottom type at which the depth is being calculated. (See ref. 7 for more details.)

It has been shown that the assumption underlying the two-band ratio method is not satisfied by Landsat TM data[7] and it has been suggested[7] that the linear multiband algorithm, with the generalized ratio assumption, may be more accurate given more bands than bottom classes, as the coefficients in the algorithm do not depend on the bottom reflectance. In this paper we use the linear multiband algorithm on two channels of a Landsat 4 TM scene and demonstrate its improved performance over the two-band ratio method.

Procedure

The Landsat scene used in this study (scene number 5032614162, taken January 21, 1985) contains Isla de Vieques, an island off the southeast coast of Puerto Rico in the Carribean Sea. The water clarity in this area is extremely good, and bottom reflectances in the blue and green channels (TM bands one and two) are detectable for depths up to 25 m. Bottom reflectances in the red channel (TM band three) are detectable for depths up to about 6 m; sensor noise (striping) over the water renders this band useless at greater depths.

The general procedure for this comparison of the three methods was first to convert a National Aeronautics and Space Administration/Goddard Space Flight Center computer compatible tapes to an image data file and to georeference this data file against a Defense Mapping Agency 1:25000 combat chart. See reference 8 for details on the georeferencing procedure. This combat chart contains not only bathymetric soundings, but also land feature identifications that aid in the georeferencing process. A set of approximately 600 calibration points was then selected by recording depths from the chart; about 300 of the points were used in our regression fit and the remaining 300 were used as a test set to check the calculated depth against the actual depth.

The average deep-water signal for each water-penetrating band (in this case channels 1 and 2, roughly corresponding to the blue-green and green portions of the visible spectrum, respectively) was calculated to obtain the $L_{i\infty}$ values.

Polygons were drawn on the image to outline the deep water (no visible ocean bottom) region in each band. The average intensity of the pixels contained in the polygon was used as the $L_{i\infty}$ values. These values are subtracted from the corresponding L_i value to adjust the signal values for atmospheric scattering, etc.

A linear regression of the model equation against the (appropriate) calibration points is run, which produces coefficients and, hence, equations for the depth Z at any pixel. The test set of calibration points is used to *test* the fit of this regression. These equations are then used to produce a bathymetric image that can be processed further (smoothed, contoured, pseudocolored, etc.) depending upon the desired application.

Results and Analysis

The linear regression was run on the equation

$$Z = A_0 + A_1 X_1 + A_2 X_2$$

corresponding to a two-channel multiband linear model. For this image we determined $L_{1\infty} = 68$ and $L_{2\infty} = 17$. The regression yielded the following values for the constants: $A_0 = 11.2, A_1 = 3.14, A_2 = -6.76$. The multiple correlation coefficient was 0.86.

Scatter plots indicated an apparent correlation of error with depth, so we plotted the test residuals of measured depth versus calibration depth for three different depth ranges, 0–5 m, 5–10 m, and 10–16 m. Residual means and RMS values are given in Table 1. It was seen that we consistently underestimated the depth in the shallower water and overestimated the depth in the deeper water.

Using the test set of calibration point data, the model yielded an overall residual mean less than 0.2 m and an overall RMS less than 1.9 m. Performing the regression in the depth range of 0–5 m, the RMS error was 0.88 m; in the range 5–10 m, the RMS error was 1.25 m; and in the range 10–16 m, the RMS error was 1.00 m.

For comparison purposes, the dual-band ratio method was applied as well. To minimize error, the image was clustered to locate areas of similar bottom reflectance using a supervised statistical clustering routine and the maximum likelihood classifier. The algorithm was then regressed against calibration points in each cluster separately. An overall residual mean of 0.093 m and an RMS error of 2.66 m was obtained (Table 2). In the depth range of 0 – 5 m, the RMS error was 0.94 m; in the range 5 – 10 m, the RMS error was 1.56 m; and in the range 10 – 15 m, the RMS error was 1.86 m.

Table 1. Errors in depth calculation from linear multiband model.

Depth Range	Residual Mean	RMS
0 – 5 m	0.002 m	0.88 m
5 – 10 m	- 0.39 m	1.25 m
10 –15 m	- 0.21 m	1.00 m
0 – 15 m	0.20 m	1.86 m

Table 2. Errors in depth calculation from dual-band ratio model.

Depth Range	Residual Mean	RMS
0 – 5 m	0.12 m	0.94 m
5 – 10 m	- 0.15 m	1.56 m
10 –15 m	- 0.25 m	1.86 m
0 – 15 m	0.10 m	2.66 m

In comparing the two methods, both algorithms underestimated the depth in shallow water and overestimated it in deeper water. This tendency produces a larger overall error than is obtained when considering the indicated depth ranges. It can be seen that the linear multiband method yields somewhat improved results, even when only two bands are available. Moreover, this method does not require the clustering and classification routines to discern areas of similar bottom reflectance, and a considerable savings in CPU processing time (one to several hours on a VAX 11/780 per 512 X 512 pixel image) is realized.

Applications

A major advantage of calculating water depths from remotely sensed data is the reduction in preparation time and in the cost of producing bathymetric charts. Moreover, the digital nature of the product lends itself to easy and rapid editing and updating.

The extrapolation of calculated bathymetric coefficients from one portion of a scene to another portion is easily accomplished due to the digital nature of the data. The authors intend to study the validity of such extrapolations in future work as this has the potential of being a major mapping, charting, and geodesy application.

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